Assessment of Ku- and Ka-Band Dual-Frequency Radar for Retrieval of Snow Properties

Liang Liao[1], Robert Meneghini[2], Ali Tokay[3], and Hyokyung Kim[1]

[1]Goddard Earth Sciences Technology & Research/MSU, Maryland
[2]NASA Goddard Space Flight Center, Maryland
[3]UMBC/JCET, Maryland

Outline

- Scattering results from simulated snow aggregates and simple (constant density) particle model using Gamma PSD
- Scattering results from simulated particles with different PSD assumptions
  - Measured PSDs with m-d_L relationship
  - Gamma PSD
  - Assess influence of different databases (FSU/GSFC), μ, m-d_L relationships
- Summary

Single Scattering Database

- Two databases are tested
  - NASA/GSFC scattering database

    Pristine crystals and aggregate snowflakes from a 3-D growth model

    Kuo, K-S, W. S. Olson, B. T. Johnson, M. Grecu, L. Tian, T. L. Clune, B. H. van Aartsen, A. J. Heymsfield, L. Liao, and R. Meneghini, 2016: The microwave radiative properties of falling snow derived from realistic ice particle models. Part I: An extensive database of simulated pristine crystals and aggregate particles, and their scattering properties. *J. Appl. Meteorol. Climatol.*,.**55**, 691-708.

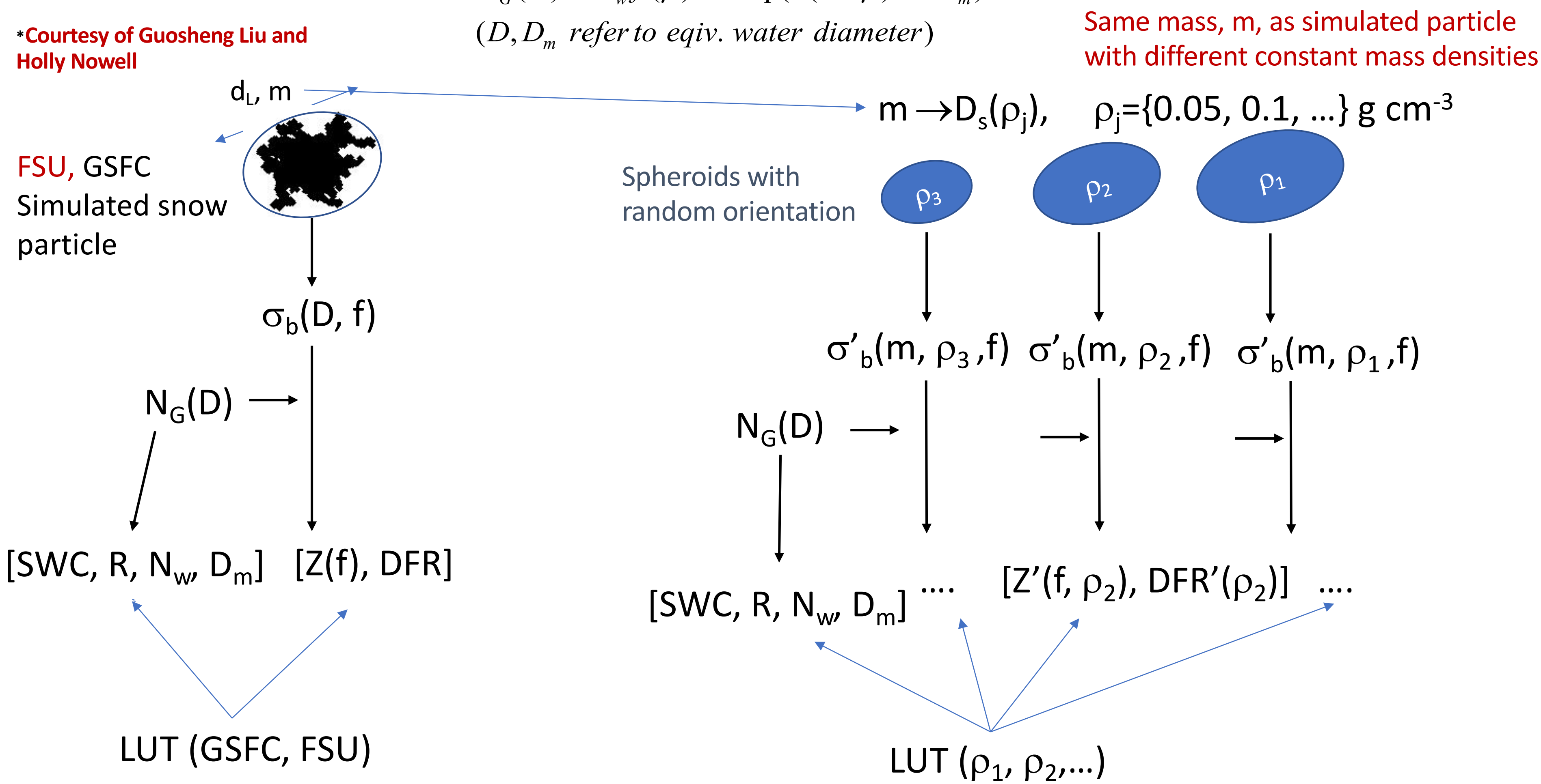
  - Florida State Univ. (FSU) database

    Aggregates comprised of 6-branch bullet rosette crystals

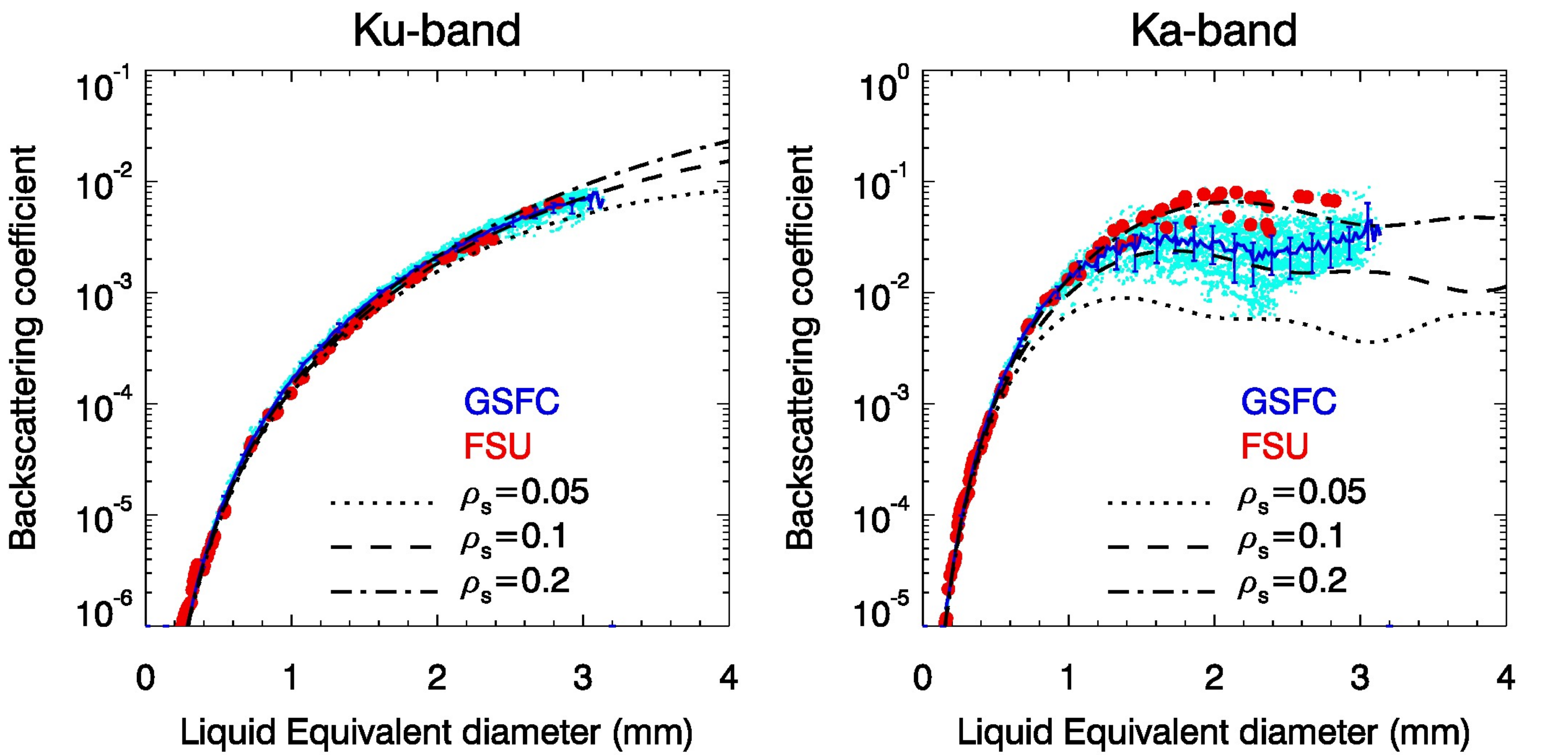
    Nowell, H., G. Liu, and R. Honeyager, 2013: Modeling the microwave single-scattering properties of aggregate snowflakes. *J. Geophys. Res. Atmos.*, 7873–7885. doi:10.1002/jgrd.50620.

$$N_G(D) = N_w f(\mu) D^{\mu} \exp(-(4+\mu)D/D_m)$$

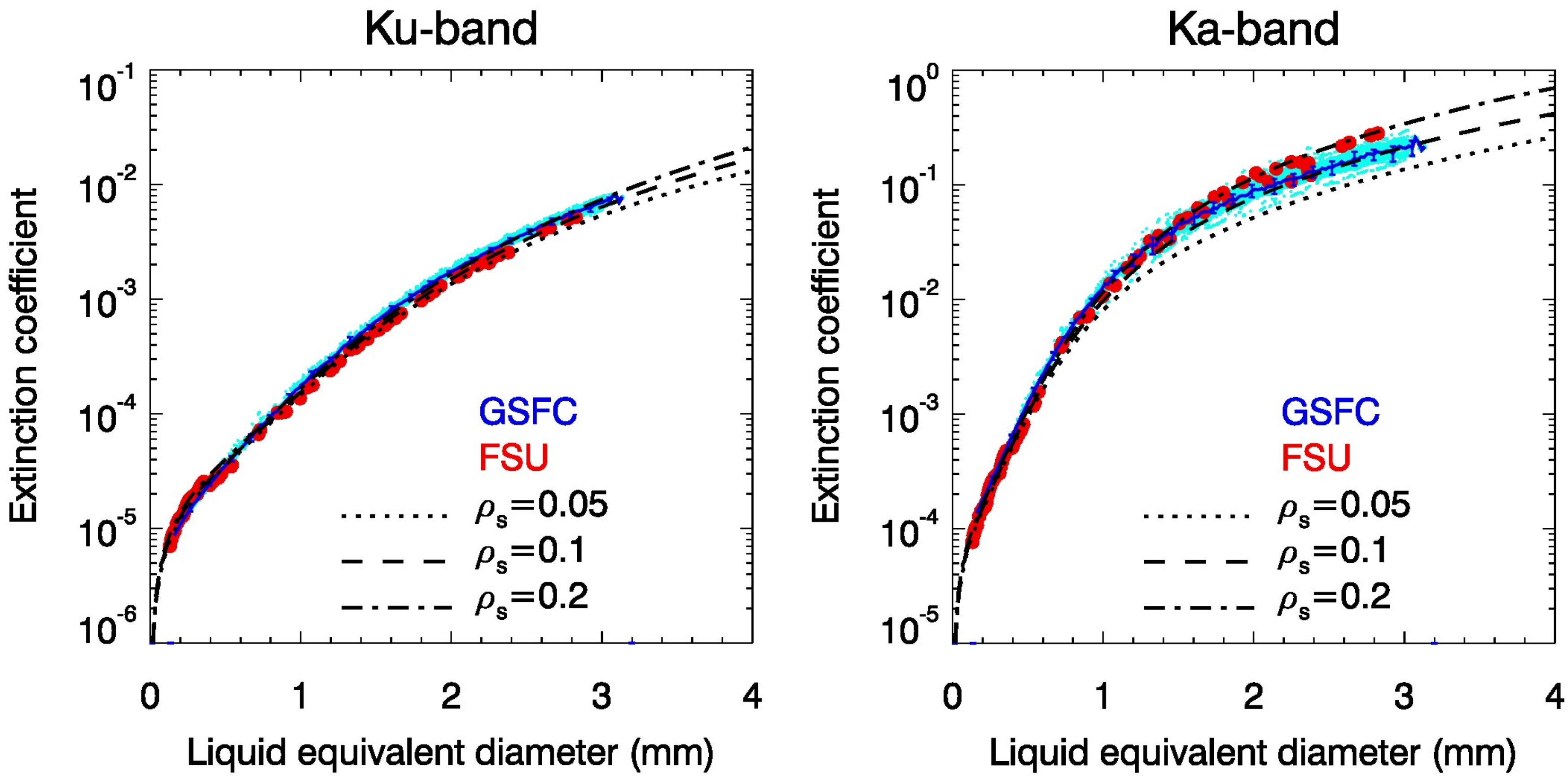
$(D, D_m$ *refer to eqiv. water diameter*$)$



Backscattering Coefficients from GSFC and FSU Scattering Database



Extinction Coefficients from GSFC and FSU Scattering Database



comments

- For FSU data set, Liao et al. (2013, 2016) showed that $\sigma_b(m, f) \approx \sigma'_b(m, \rho, f)$ if $\rho \approx 0.2$ g cm^{-3}
  - for Ku-band and Ka-band (some discrepancies at W-band)

- This is the case not only for the backscat. cross section but other scattering parameters as well

- For GSFC data set [Kuo et al., 2016], it appears that $\sigma_b(m, f) \approx \sigma'_b(m, \rho, f)$ if $\rho \approx 0.1$ g cm^{-3}

- If backscattering cross sections are approx. the same for simulated and fixed density particles for $\rho=\rho^*$, then $[Z(f), DFR]_{sim} \approx [Z'(f, \rho^*), DFR'(\rho^*)]$ as long as the PSD is the same in the two cases

Dual-λ Retrieval Technique

Assuming liquid-equivalent PSD: $$N(D) = N_W f(\mu)\left(\frac{D}{D_m}\right)^{\mu} \exp(-\Lambda D),$$

Radar reflectivity factor: $$Z_e = \frac{\lambda^4}{\pi^5 |K_w|^2} \int_0^{\infty} N(D)\sigma_b(D,\lambda) dD,$$

Differential frequency ratio (DFR): $$DFR = 10\log(Z_{Ku}/Z_{Ka})$$

Snow water content: $$SWC = \int_0^{\infty} N(D)m(D)dD$$

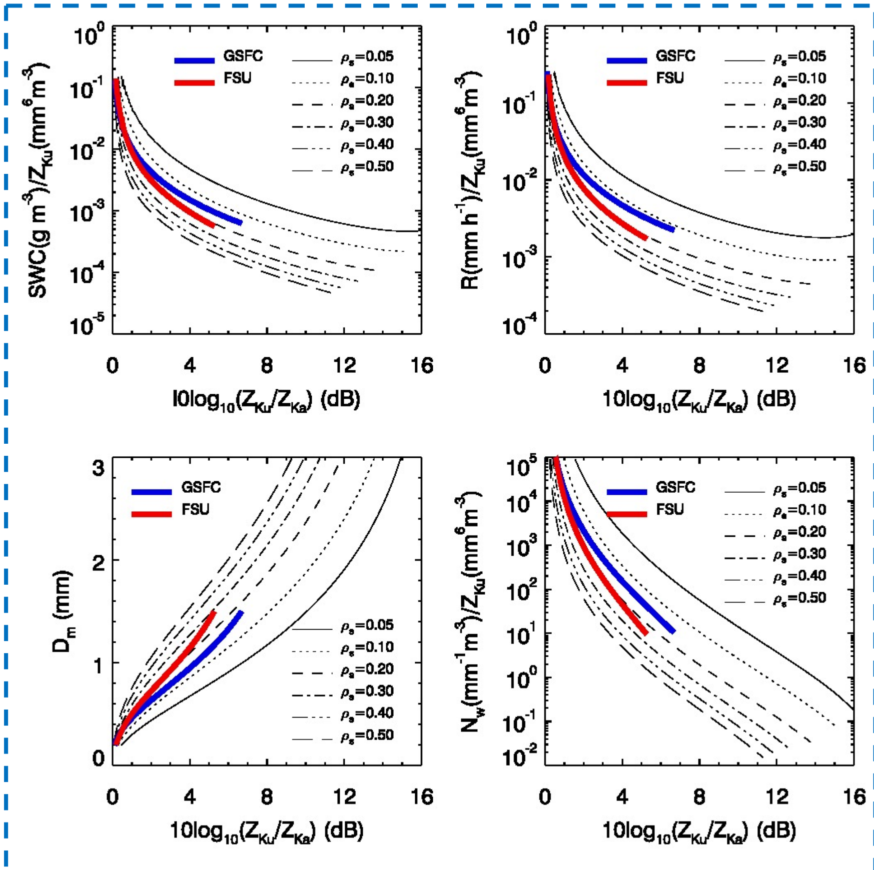
Liquid-equivalent snow rate: $$R = \frac{36\times 10^{-4}}{\rho_w} \int_0^{\infty} N(D)m(D)V(D)dD$$

Thus, for fixed μ and known v-D

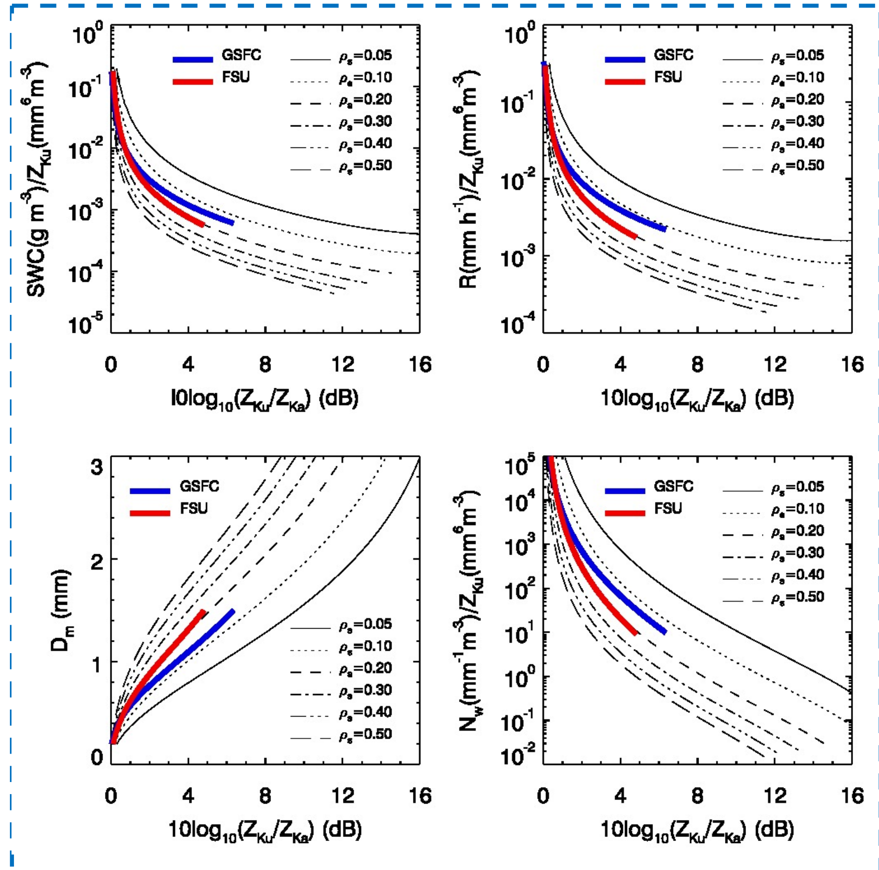
$SWC / Z_{Ku} = f_1(DFR)$, $R / Z_{Ku} = f_2(DFR)$, $D_m = f_3(DFR)$, $N_w / Z_{Ku} = f_4(DFR)$

Snow Retrieval LUT Based on Scattering Database

μ=0



μ=3



Issues Related to Snow Retrieval

- Snow microphysical models include
  - PSD model, particularly snow mass spectra
    - Because direct/reliable measurements of mass or D_{eq}(water) are usually not available, the snow mass spectrum (liquid-equivalent PSD) is usually obtained by converting the distribution of max dimension of particles (L) to mass or D_{eq}(water) by an empirical mass-size relation (m-L or m-D)
    - There are, however, different ways of doing this which results in some ambiguities in the analysis.
  - Snow particle models (shape, orientation and composition)

    Highly variable in nature but critical for computing higher frequency radar parameters.
- Electric scattering properties of snowflakes

  These depend on single scattering models that account for shape, orientation and structure [as well as numerical methods for computations].

Objectives

- To characterize the errors (bias and variance) in estimates of liquid-equivalent PSD parameters (D_m & N_w) and bulk parameters (SWC and R) from dual-wavelength radar techniques in association with
  - gamma PSD model (with various μ values)
  - m-d_L relationship (sensitivity of m-d_L to assessment procedures)
  - scattering database (on which the retrievals depend)
- Find an appropriate (or best) PSD model to estimate the PSD and snow bulk properties of interest.

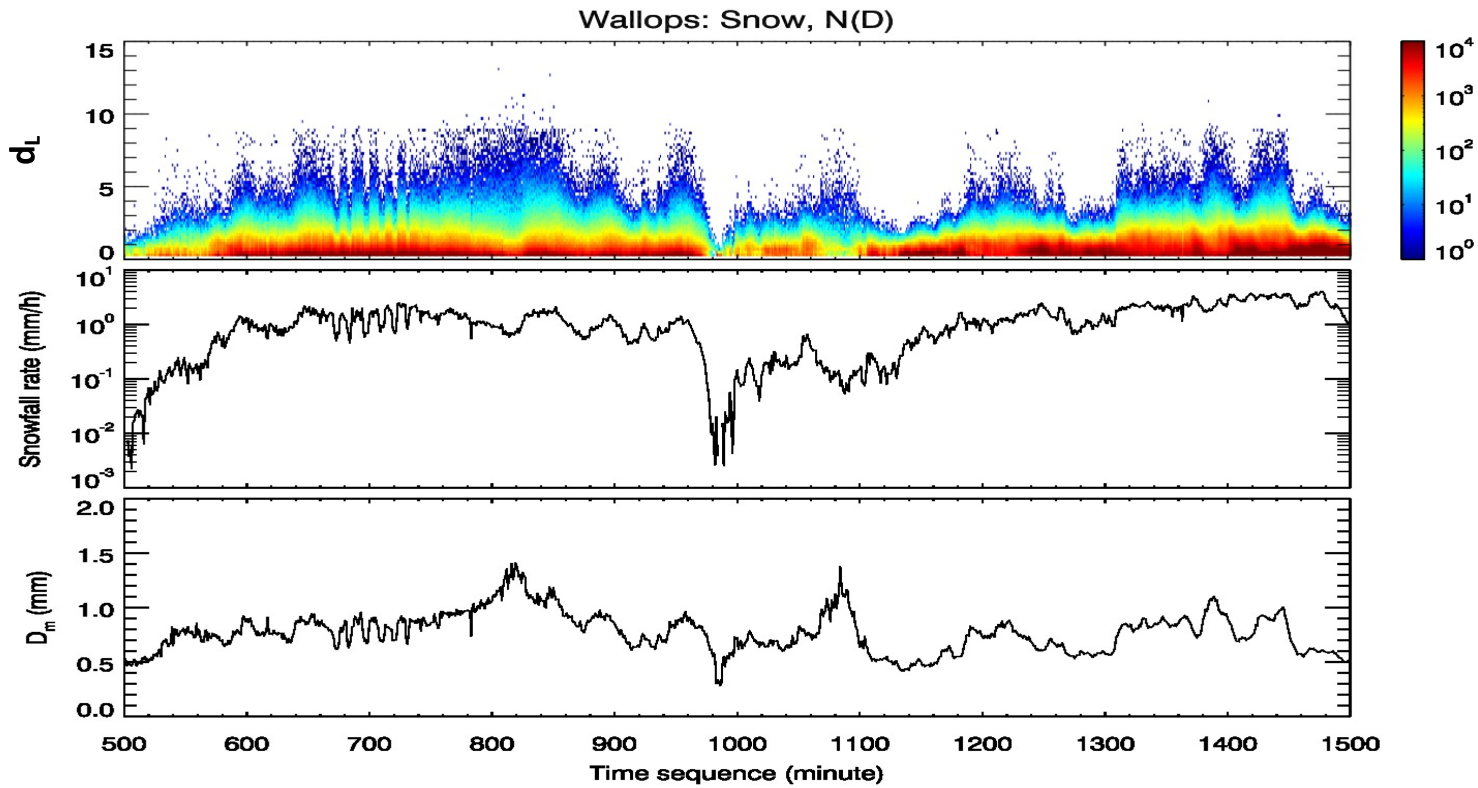
To test impact of the m-d_L relations used for converting measured PSD to snow mass spectra on retrieval, three popular m-d_L relations are employed, which are documented by

Heymsfield, A. J., C. Schmitt, A. Bansemer, and C. H. Twohy, 2010: Improved representation of ice particle masses based on observations in natural clouds. *J. Atmos. Sci*., **67**, 3303–3318.

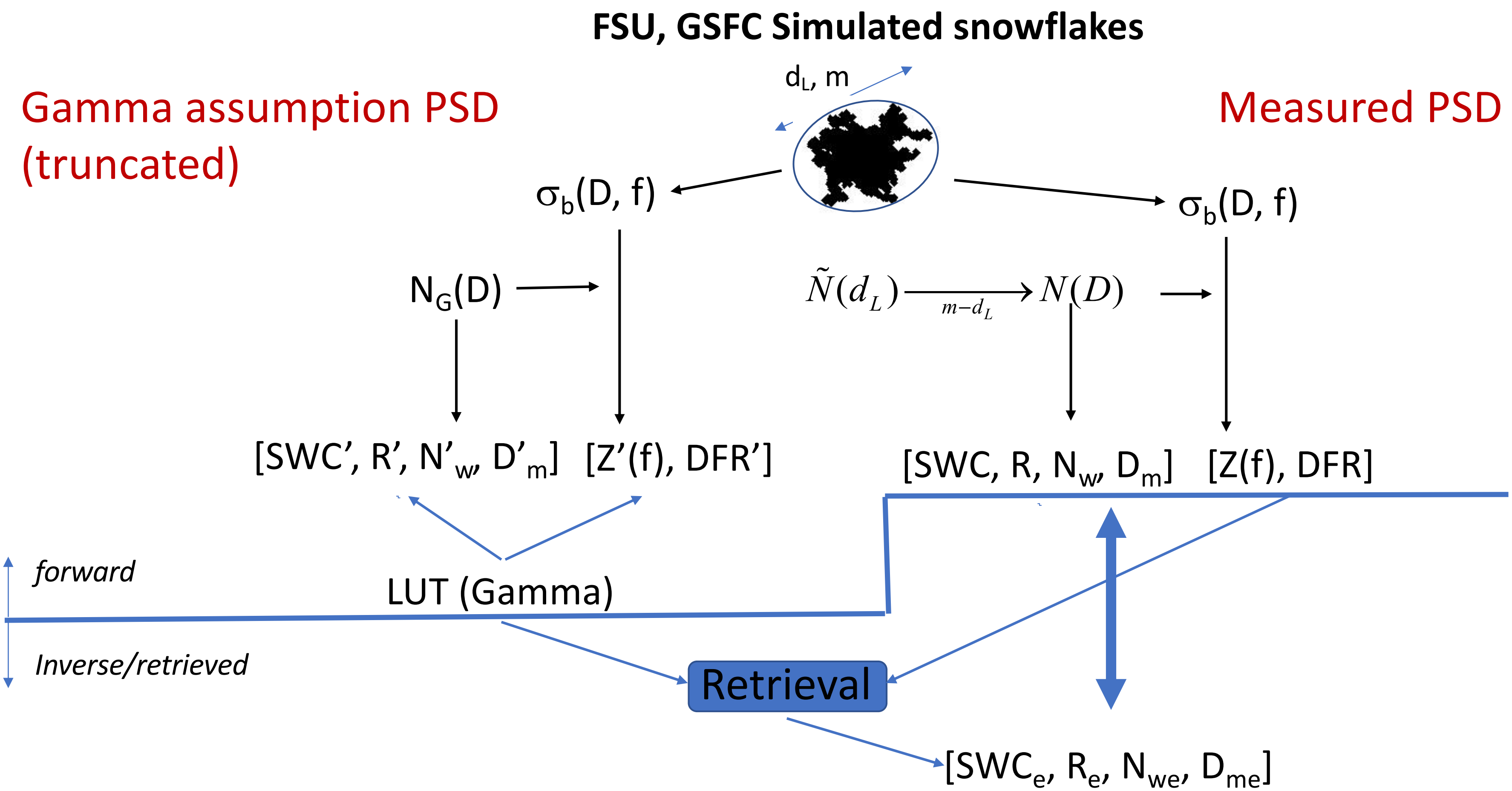
Brandes, E., K. Ikeda, G. Zhang, M. Schoenhuber, and R. Rasmussen, 2007: A statistical and physical description of hydrometeor distributions in Colorado snowstorms using a video distrometer. *J. Appl. Meteor. Climat*., **46**, 634-650.

Fabry, F., and W. Szyrmer, 1999: Modeling of the melting layer. Part II: Electromagnetic, *J. Atmos. Sci*., **56**, 3593–3600.

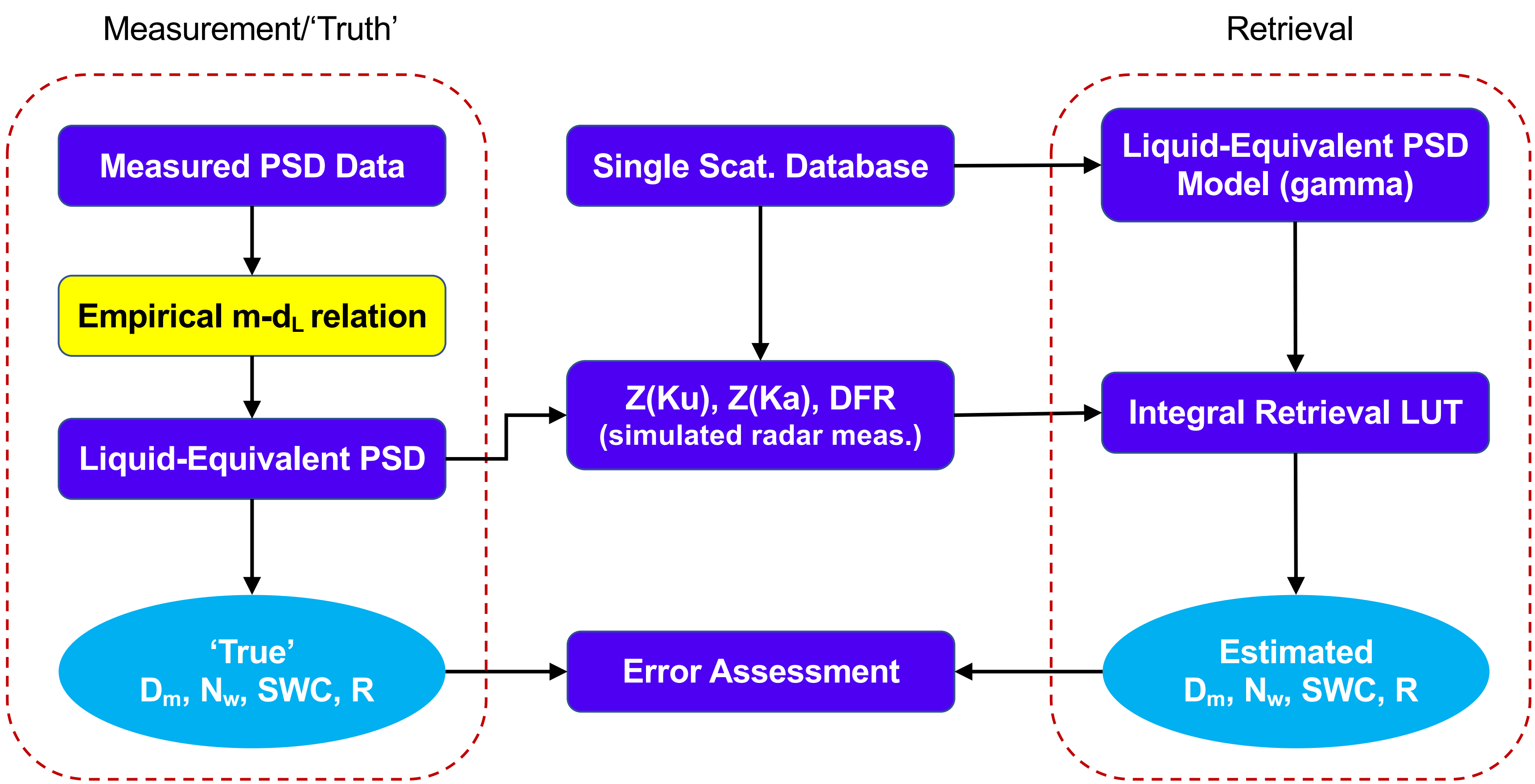
Example of PSD Measurements



Example of a segment of the PSD data, obtained by averaging the measurements over 1-minute integration time, in time series taken from 8 snow events during winter of 2014 at the NASA Wallops Flight Facility using the SVI/PIP. The particle size spectra (mm^{-1} m^{-3}), shown in the color scale, are given in the top panel while equivalent snow fall rate and median mass diameter are displayed in the middle and bottom panels, respectively.

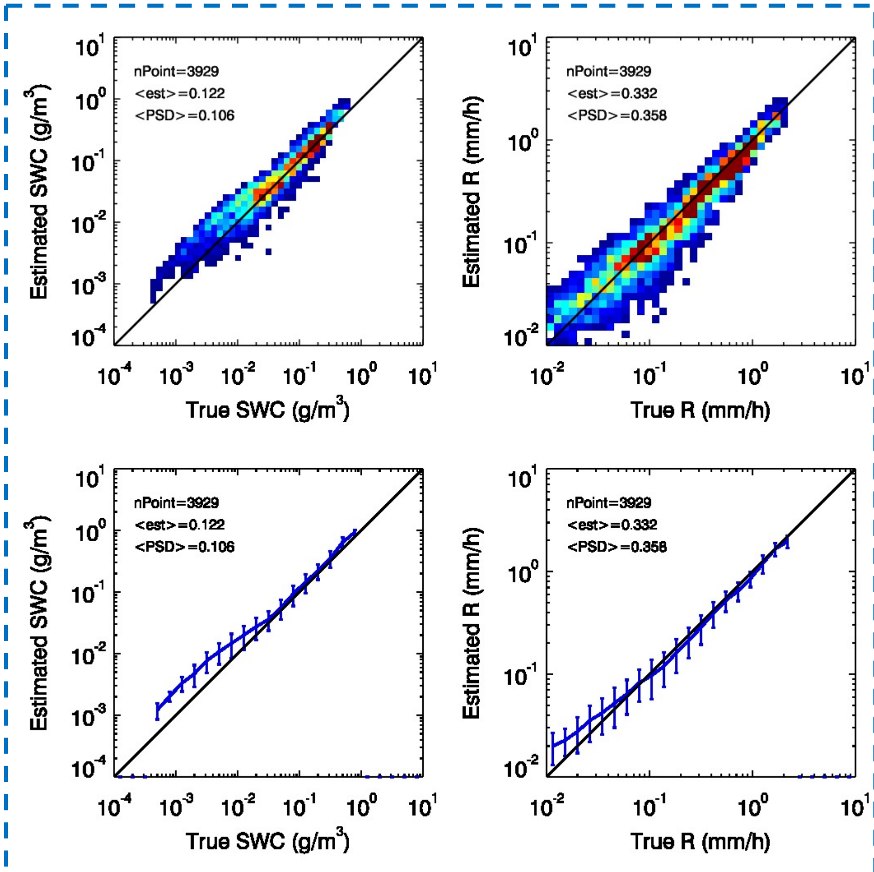

FSU, GSFC Simulated snowflakes
d_L, m
Gamma assumption PSD (truncated)
Measured PSD
σ_b(D, f)
σ_b(D, f)
N_G(D)
$\tilde{N}(d_L) \xrightarrow[m-d_L]{} N(D)$
[SWC', R', N'_w, D'_m] [Z'(f), DFR']
[SWC, R, N_w, D_m] [Z(f), DFR]
forward
LUT (Gamma)
Inverse/retrieved
Retrieval
[SWC_e, R_e, N_{we}, D_{me}]

Approach

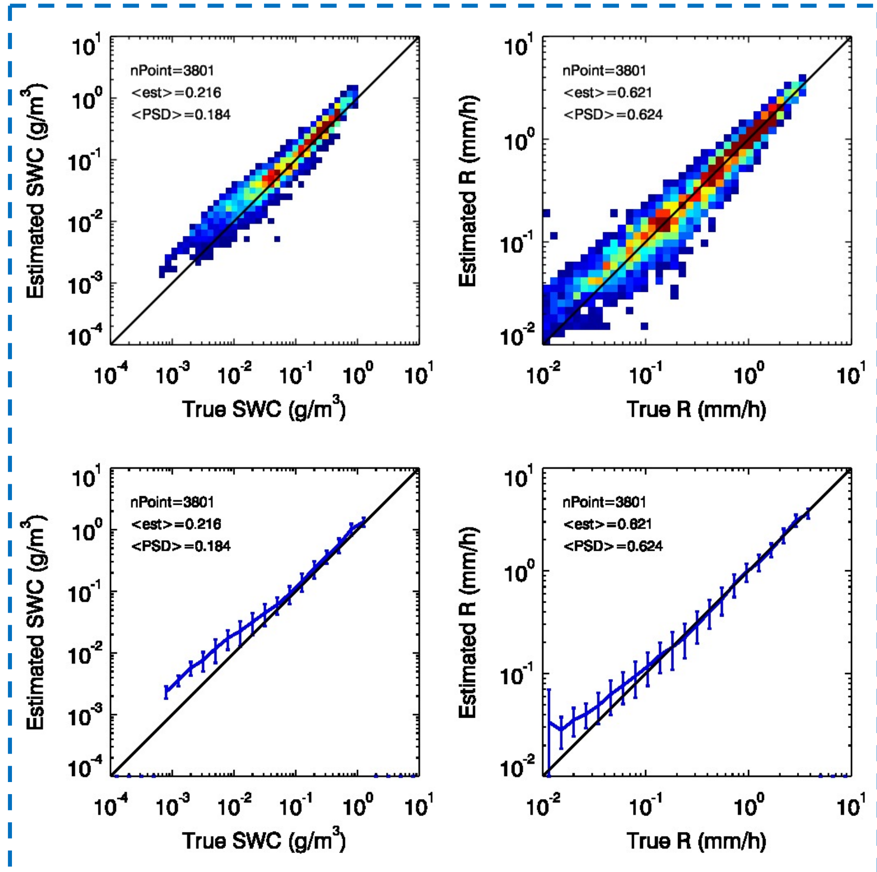

Measurement/'Truth'
Retrieval
Measured PSD Data
Empirical m-d$_L$ relation
Liquid-Equivalent PSD
'True' D_m, N_w, SWC, R
Single Scat. Database
Z(Ku), Z(Ka), DFR (simulated radar meas.)
Error Assessment
Liquid-Equivalent PSD Model (gamma)
Integral Retrieval LUT
Estimated D_m, N_w, SWC, R

Comparisons between Estimated and True SWC & R (μ=0 & GSFC-LUT)

m-d_L (Heymsfield 2010)

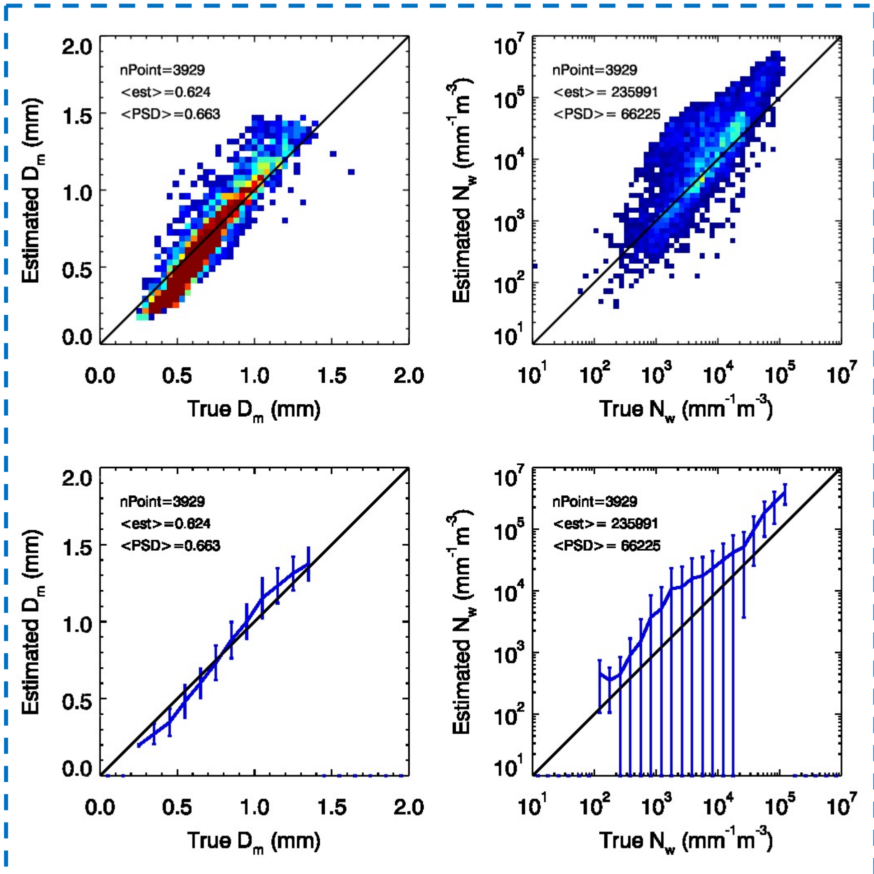


m-d_L (Brandes 2007)

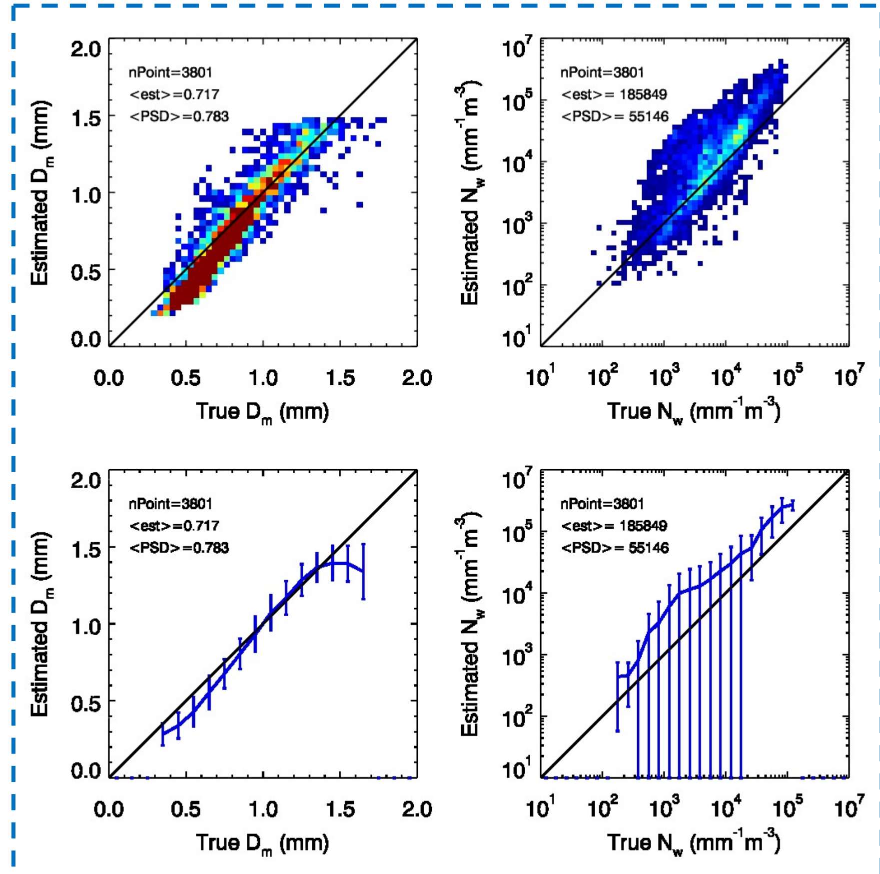


Comparisons between Estimated and True D_m & N_w (μ=0 & GSFC-LUT)

m-d_L (Heymsfield 2010)



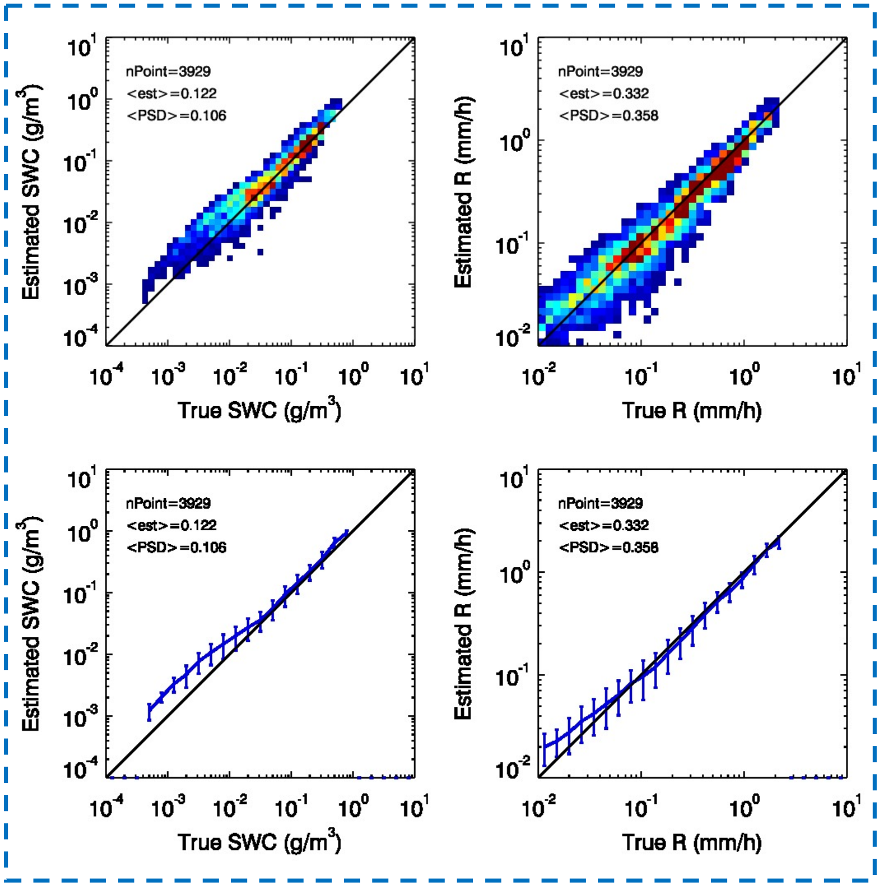
m-d_L (Brandes 2007)



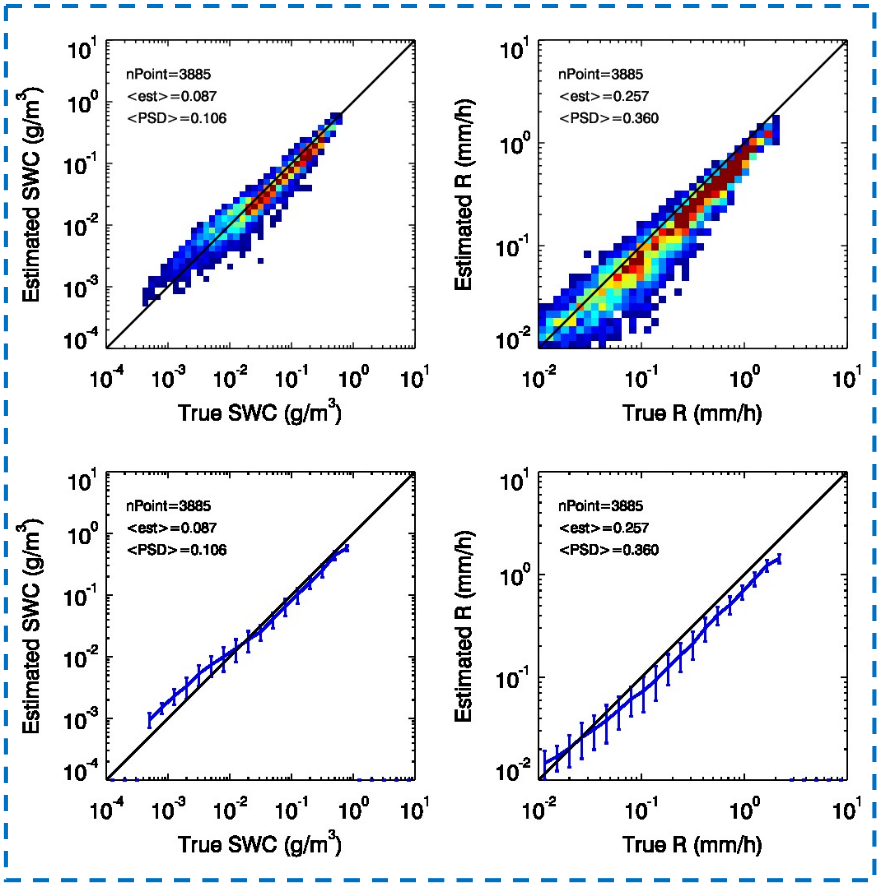
To test impact of μ …

Comparisons between Est. and True SWC & R (Heymsfield m-d_L & GSFC-LUT)

μ=0

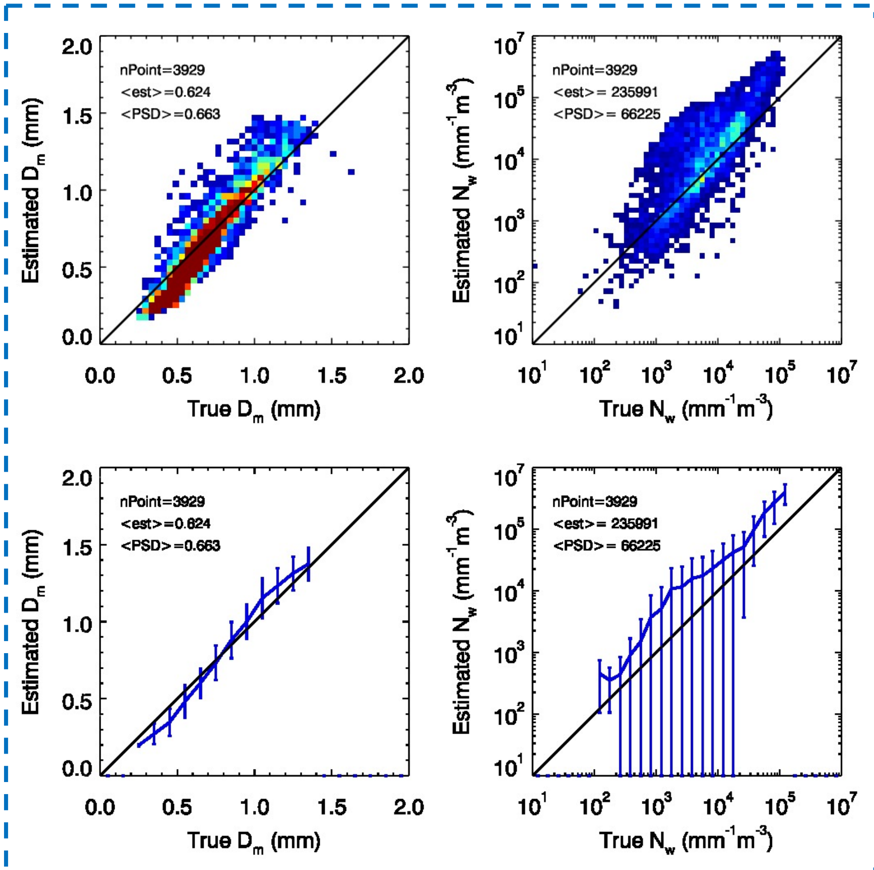


μ=3

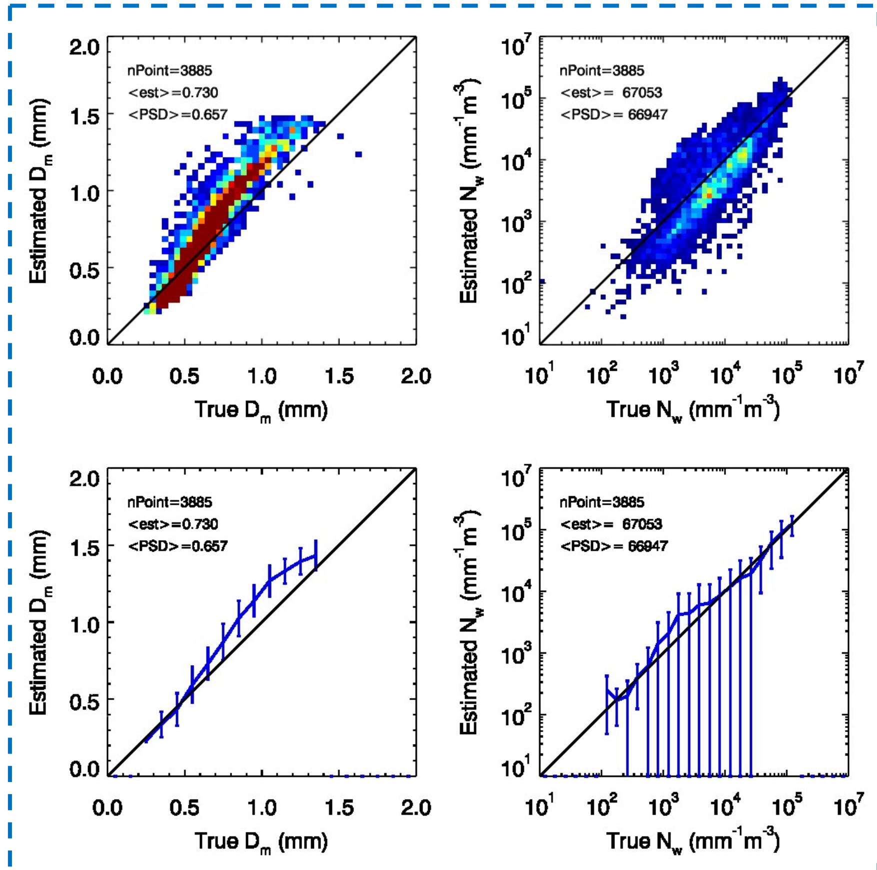


Comparisons between Est. and True D_m & N_w (Heymsfield m-d_L & GSFC-LUT)

μ=0



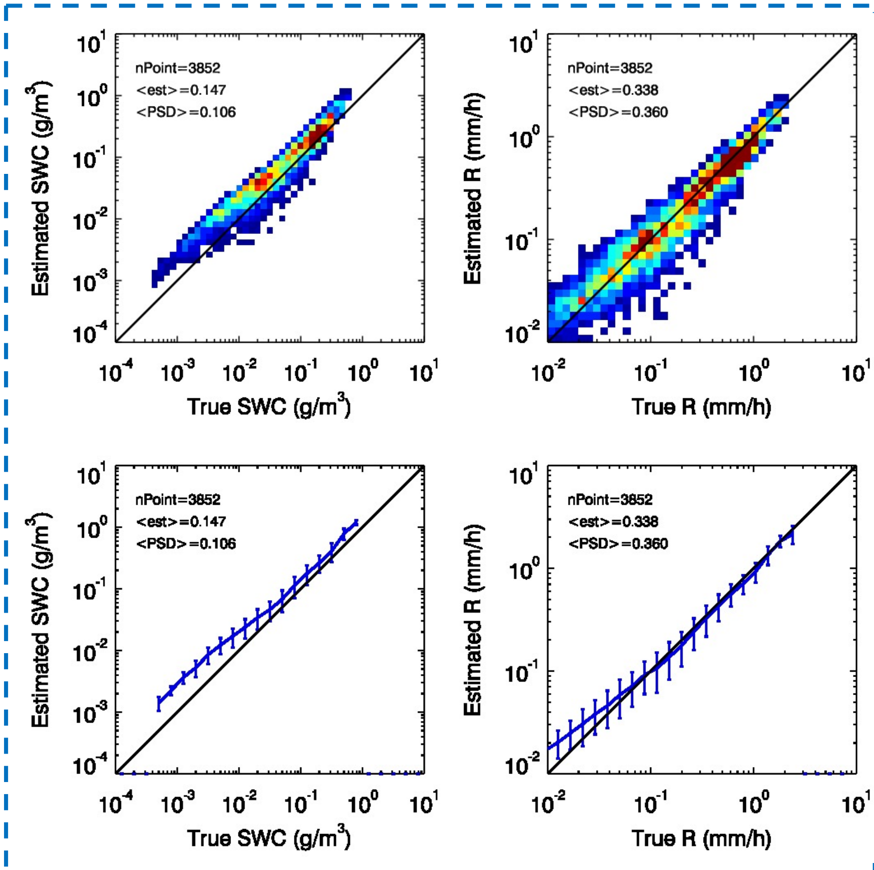
μ=3



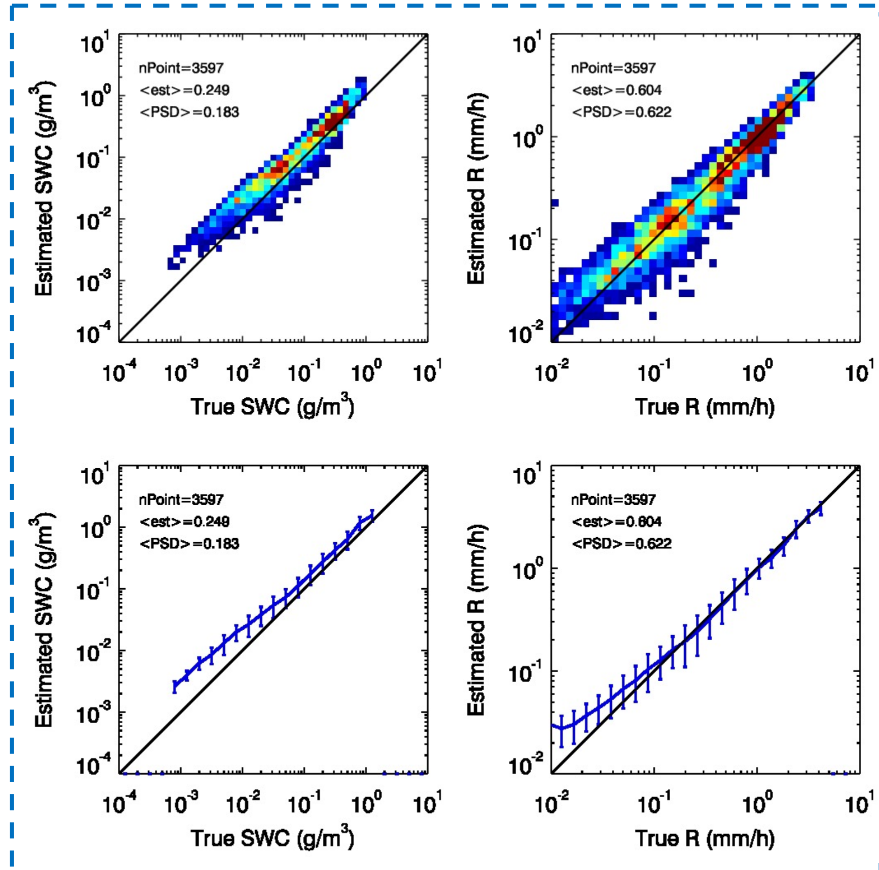
For the case in which GSFC scattering database is replaced by FSU database (same scattering tables are used for generating measured reflectivities and for the retrievals), …

Comparisons between Estimated and True SWC & R (μ=0 & FSU-LUT)

m-d_L (Heymsfield 2010)

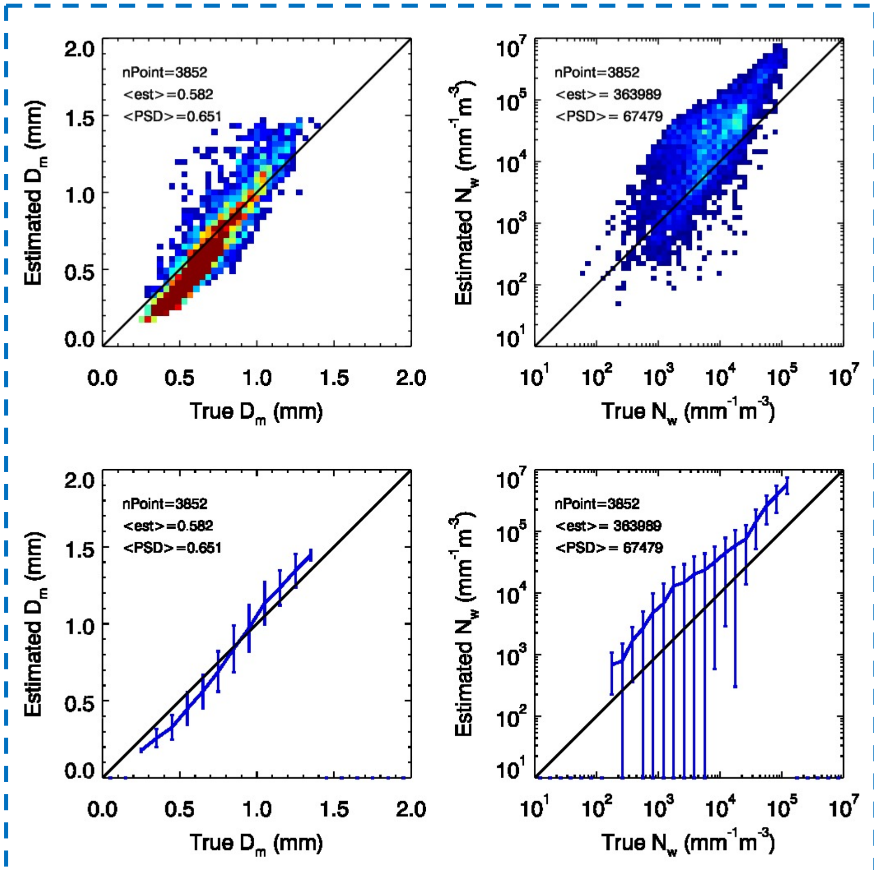


m-d_L (Brandes 2007)

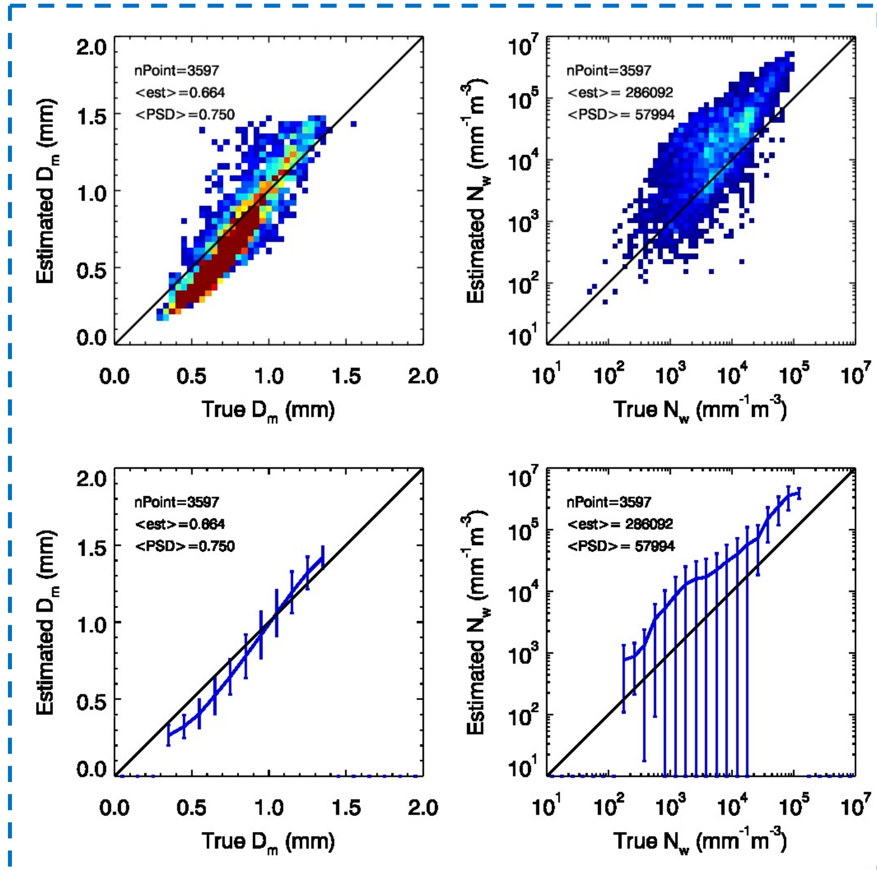


Comparisons between Estimated and True D_m & N_w (μ=0 & FSU-LUT)

m-d_L (Heymsfield 2010)

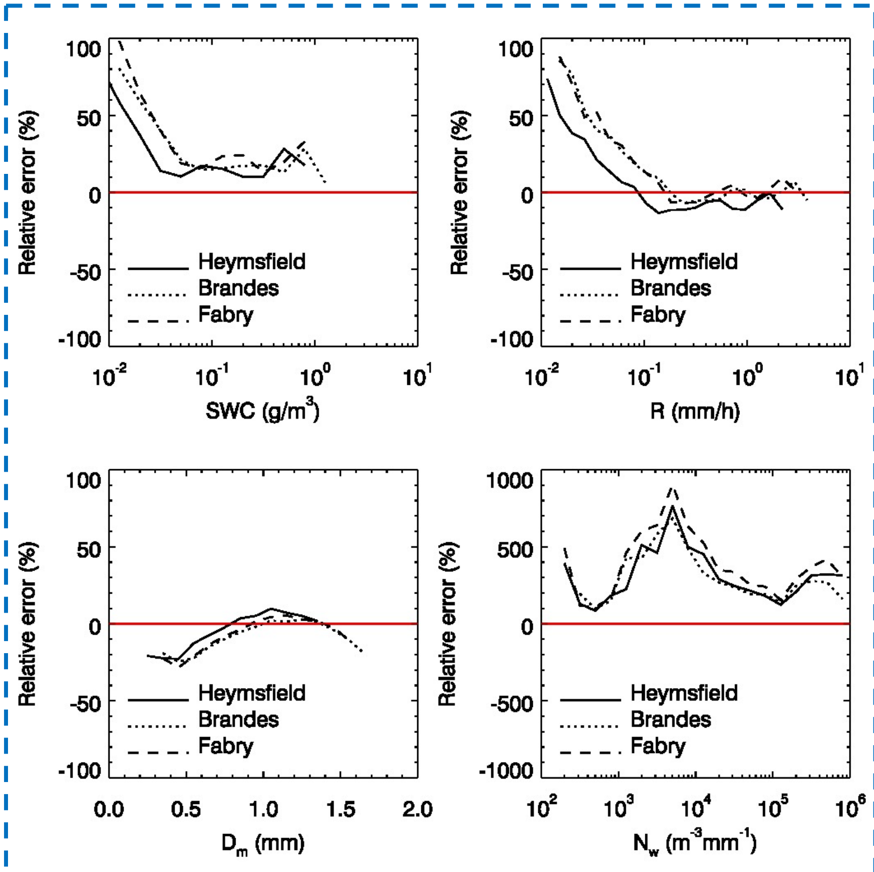


m-d_L (Brandes 2007)

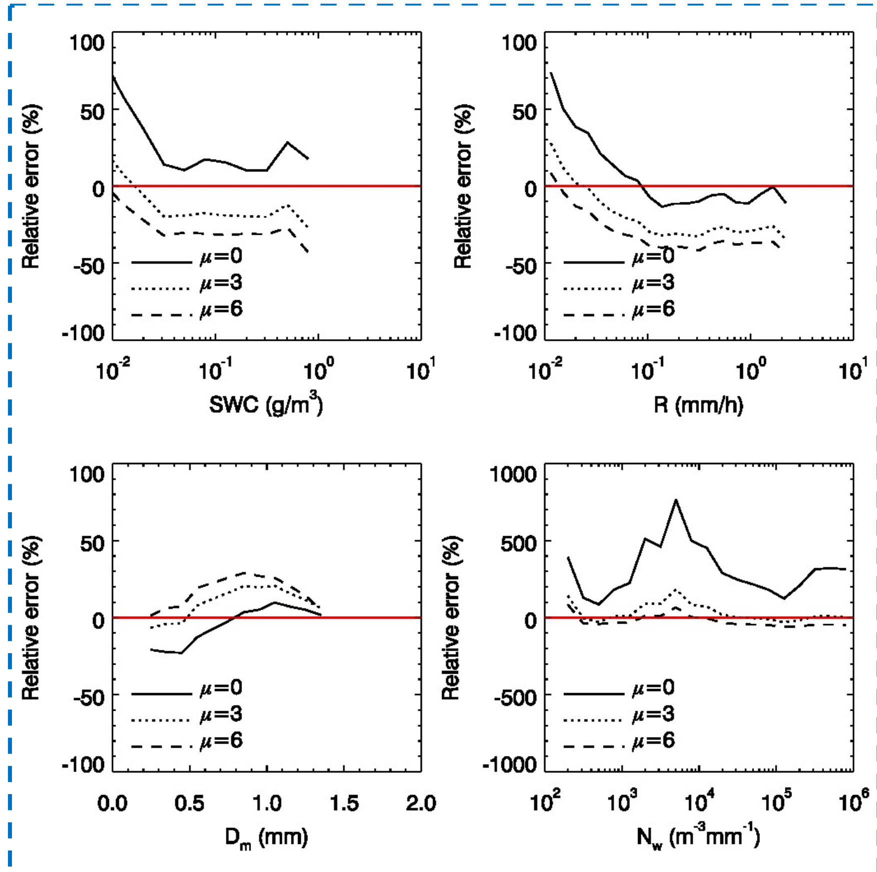


Relative Errors of Estimates (GSFC-LUT)

For several m-d_L relations (μ=0)



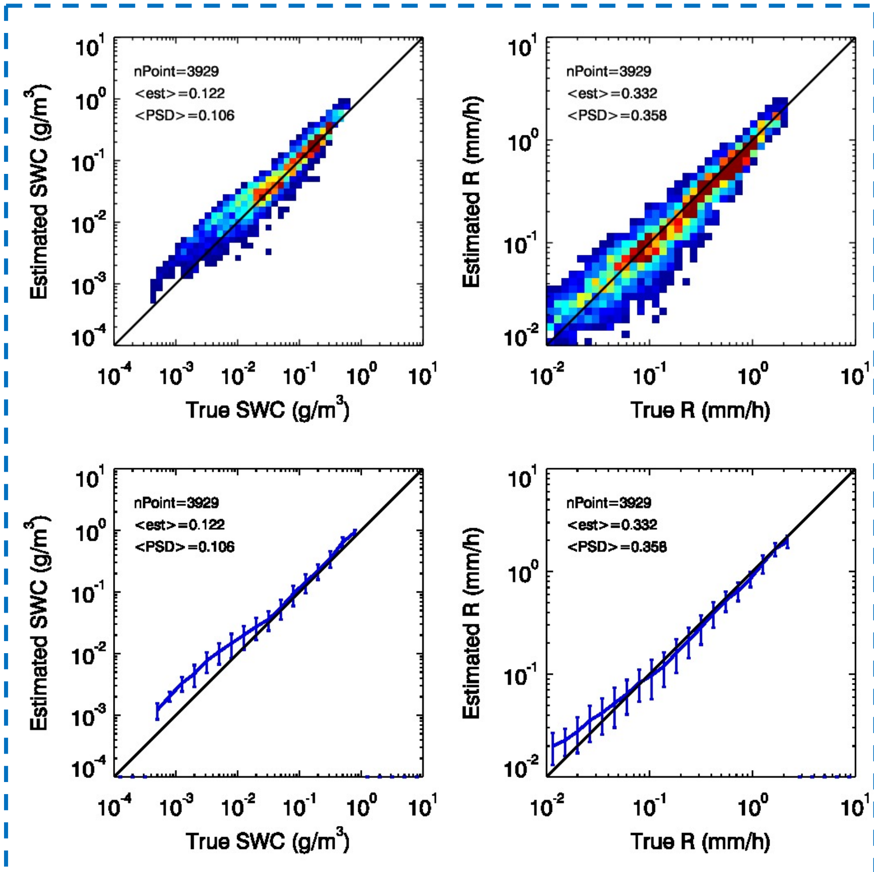
For several μ (Heymsfield m-d_L)



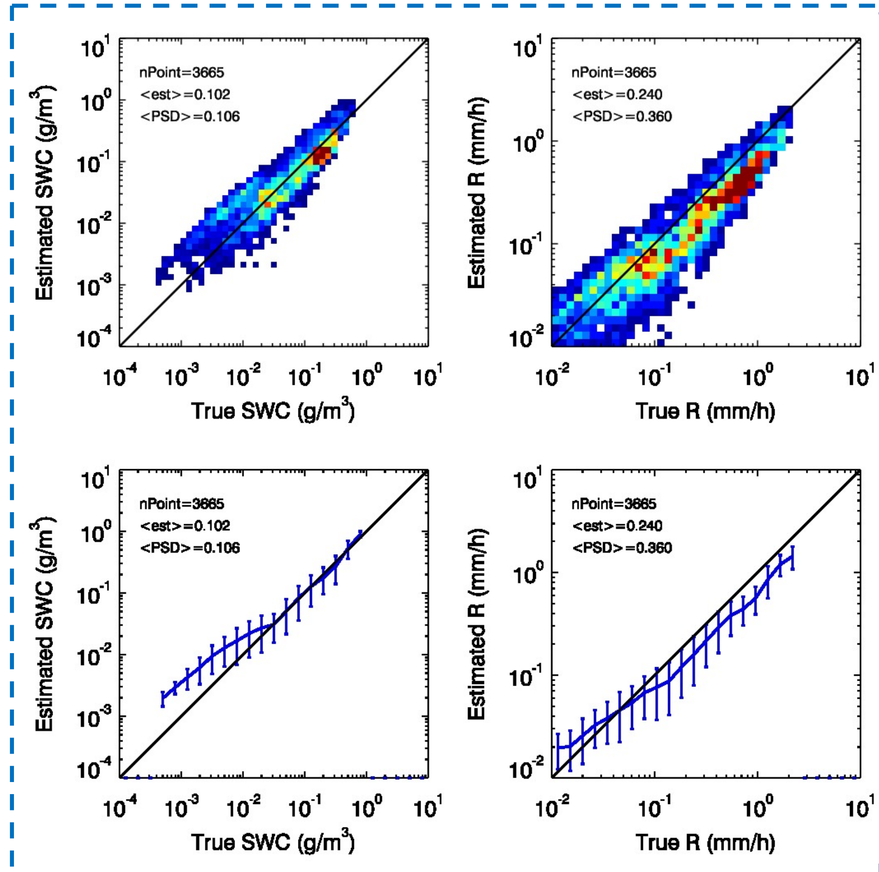
For the case in which measured reflectivities are generated by one scattering table (e.g., GSFC-LUT) and retrievals are made by another (FSU-LUT)…

Comparisons between Est. and True SWC & R (μ=0 & Heymsfield m-d_L)

GSFC-LUT for Z_m and estimates

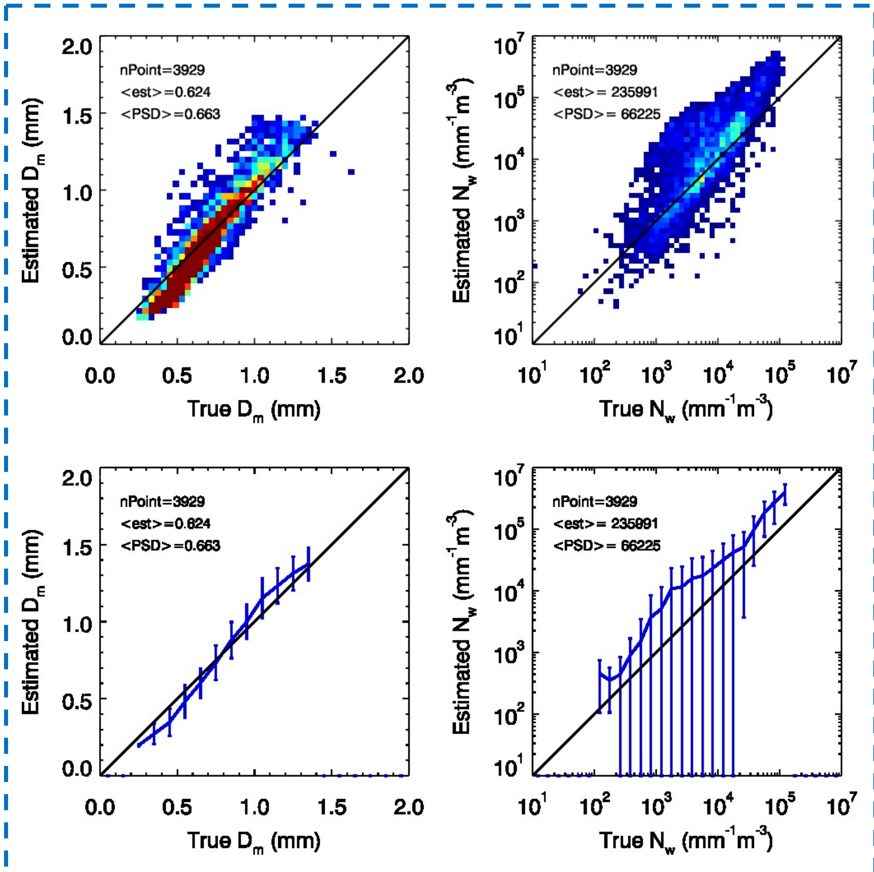


GSFC-LUT for Z_m & FSU-LUT for estimates

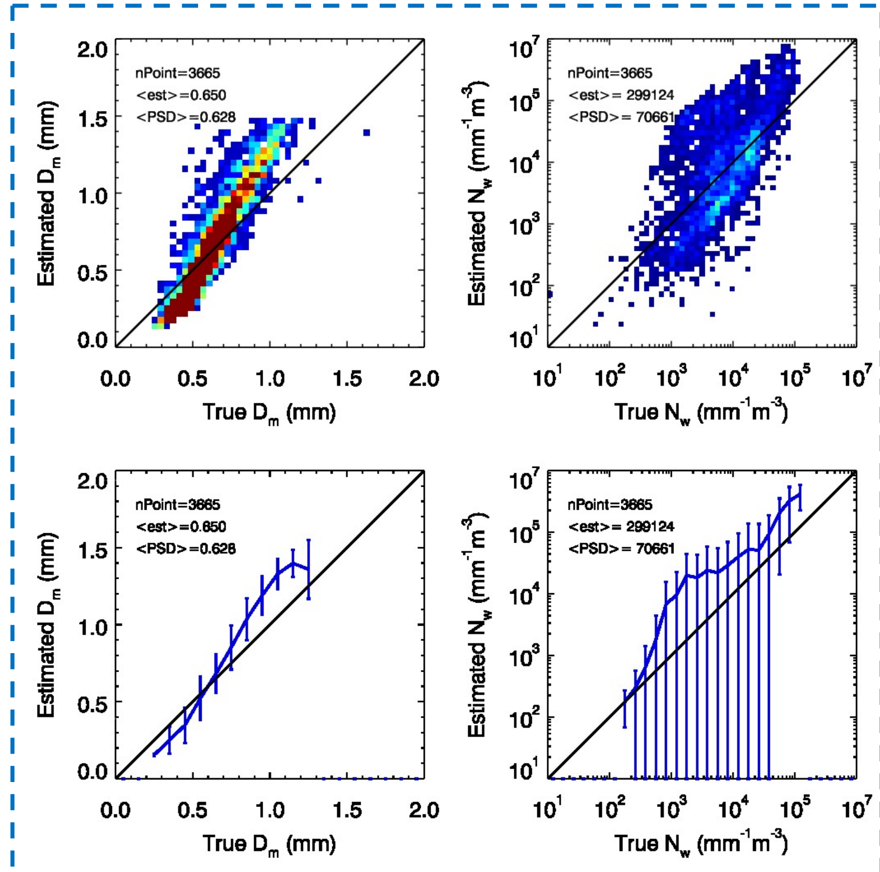


Comparisons between Est. and True D_m & N_w (μ=0 & Heymsfield m-d_L)

GSFC-LUT for Z_m and estimates

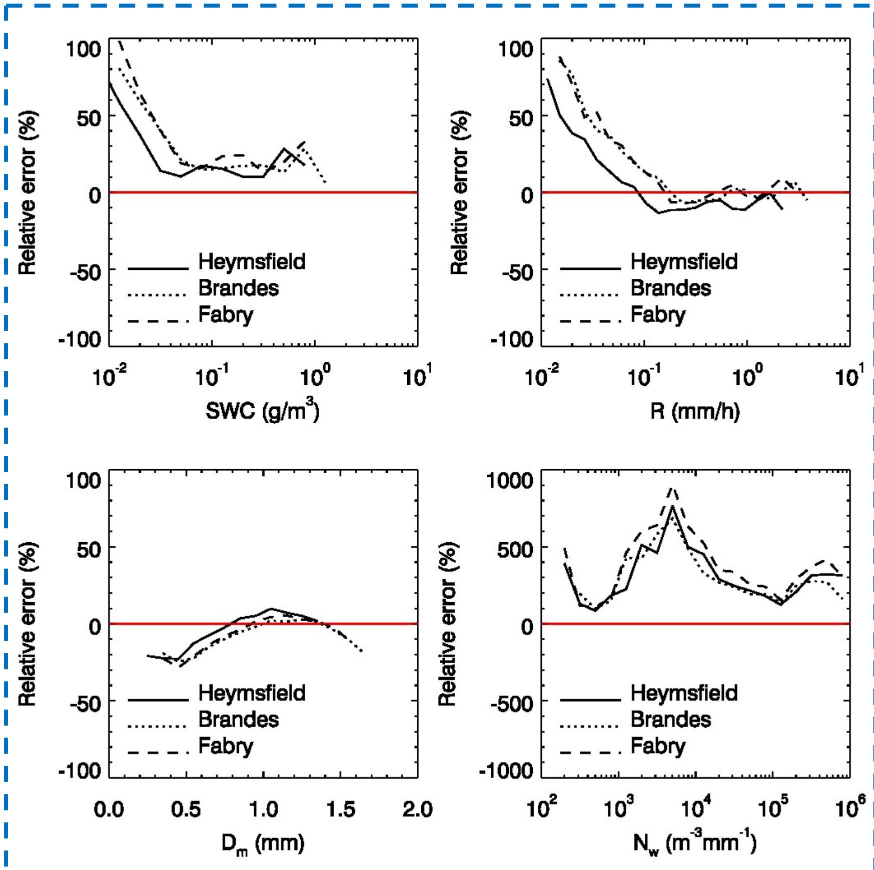


GSFC-LUT for Z_m & FSU-LUT for estimates

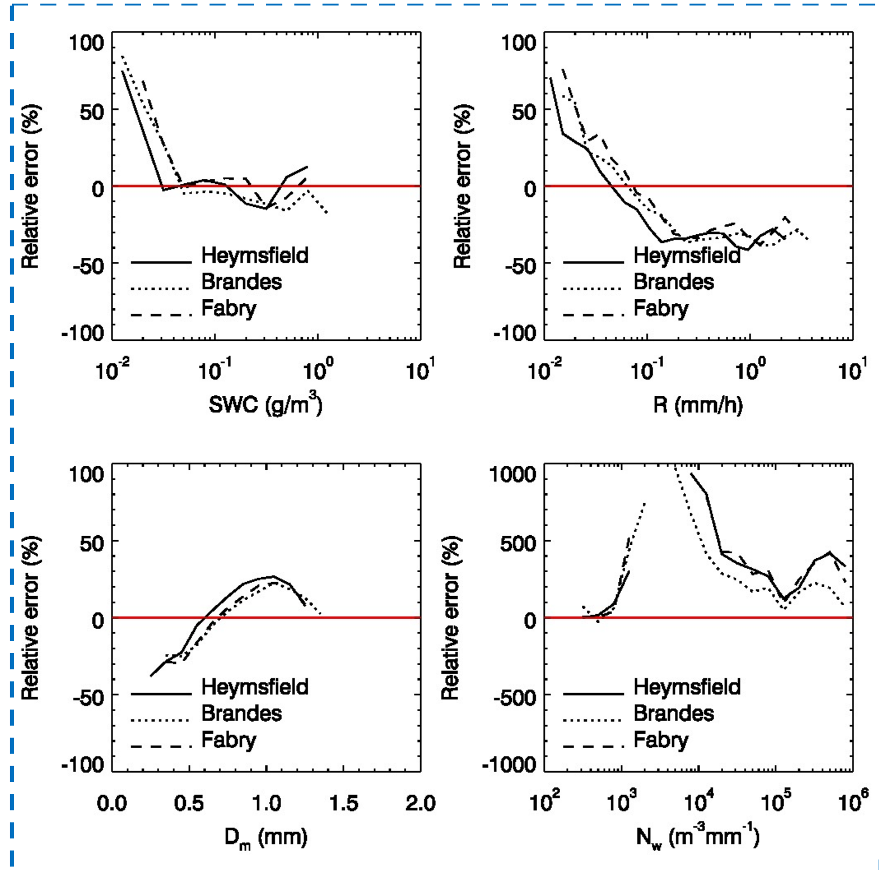


Relative Errors of Estimates (μ=0)

GSFC→Z_m & GSFC→SWC, R, D_m, N_w



GSFC→Z_m & FSU→SWC, R, D_m, N_w



Remarks

- To understand and characterize biases and variances of snow parameters (SWC, R, D_m and N_w) derived from dual-frequency radar, we need to evaluate separately uncertainties associated with PSD models and scattering models.
- As snow is assumed to obey a gamma distribution, retrieval accuracy has been assessed using measured snowflake size spectra converted to mass spectra by using empirical m-d_L relations. In the evaluation procedures, the same scattering database is employed to simulate radar reflectivities and to infer snow properties. It is found that:
  - Retrieval accuracy is not sensitive to the m-d_L relation chosen (of the 3 considered)
  - Values of μ have various impacts on snow retrieval, e.g., there is less bias in estimates of snowfall rate when μ=0 but better agreement of N_w with the true values (PSD directly derived) is achieved when μ=3.
    - Less than 10% and 30% negative biases in R estimates when μ=0 and 3, respectively.
  - Above findings are not affected by the scattering databases (GSFC/FSU) selected as long as same scattering tables are used for generating radar parameters and for snow retrieval.

Remarks (Cont'd)

- It is difficult to assess scattering models without collocated measurements of dual-frequency radar and snow mass spectra or bulk snow properties (SWC and R).
- Radar backscattering cross sections from single scattering models of snow in principle depend on shapes, orientations and structures of snow, which are more important at Ka-band than at Ku-band.
- GSFC and FSU scattering databases, although both of which nearly depict identical scattering radar cross sections at Ku band, show some differences in scattering properties at Ka-band. This leads to an increase in the bias of snow estimates if one scattering database is used for simulating radar measurements and another for snow retrieval.
- The largest snow particles included in both GSFC and FSU databases are up to liquid-equivalent diameters around 3 mm, which, though it covers most of snow particle sizes for light to moderate snowfall rates, may result in truncation errors for relatively heavy snow. This is evidenced by the fact that DFR computed from measured PSD using both databases rarely exceed 8 dB, which is well below measurements from aircraft radar and GPM DPR. Desirable databases should include larger particles up to 5-6 mm in liquid-equivalent diameters.

Future Work

- Extensive PSD data, such as Parsivel measurements from the ICE-POP 2018, will be included in this study to check consistency of our findings.
- Exploring collocated dual-frequency radar and snow measurements for accurate assessment of scattering databases.